nomical time] and to have ended at 03 h 45 m 26 s apparent time.

'Mr. George Witchell had exact observations of the same eclipse taken at Oxford by the Rev. Mr. Hornby, and . . . from the comparison the difference of longitude of the places of observation, making due allowance for parallax and the Earth's spheroidal figure, was computed. . . .'

Cook's place of observation became known as Eclipse Island and, according to his eclipse observations, its longitude was found to be 57° 36′ 30″ W. In 1874 the longitude of the same spot was found by means of electric telegraph to be 57° 36′ 52″, which speaks highly of the accuracy of the observations made by Cook and Hornby.

We are informed by Andrew Mackay, in his *Theory of the Longitude* of 1793, that the method of finding longitude from solar eclipse observations is:

'. . . the most accurate of any that has hitherto been employed. The difference of the meridians of two places may be found to the nearest second of time by comparing corresponding observations of the same eclipse.'

3. LONGITUDE FROM OBSERVATIONS OF JUPITER'S SATELLITES

A second astronomical method for finding longitude employed the satellites of Jupiter. Jupiter's four principal satellites were first observed in 1610 by Galileo, the famous mathematical professor of Padua.

The orbits of the satellites of Jupiter* are very nearly co-planar with the equator of Jupiter. The length of Jupiter's shadow cast by the Sun is about 600 times his diameter, whereas the distance of the outermost satellite is a mere 13 diameters from its parent planet. Consequently the satellites, in their orbital movements, are eclipsed. Jupiter's distance from the Sun is about five times the Earth's distance from the Sun; and the plane of Jupiter's orbit makes an angle of only about 1½° to the plane of the ecliptic. Therefore, the times of eclipses of the satellites are almost unaffected by the location of an observer on the Earth.

* Jupiter has at least twelve satellites although only four are relatively bright ones which are plainly visible through a ship's long glass.

The satellite nearest to Jupiter is called the First Satellite; the next the Second Satellite, and so on. The First Satellite makes one orbital revolution in 42 hours. The periods of the Second, Third and Fourth Satellites are 85, 170, and 400 hours respectively.

There are four different effects visible from the Earth: eclipses, occultations, transits of satellites, and transits of satellites' shadows. An eclipse occurs when a satellite enters Jupiter's shadow, and an occultation occurs when Jupiter himself hides a satellite. A transit of a satellite occurs when the satellite comes between the Earth and Jupiter, in which event the satellite appears as a tiny dark spot on the face of the planet. The entrance of the spot on the disc of Jupiter is called its ingress, and its leaving the disc, its egress. The transit of a shadow of a satellite occurs when the satellite lies on the straight line joining the satellite and the Sun.

There being four principal satellites and four effects for each satellite, the frequency of occasions when observations of the satellites may be made for the purpose of finding longitude is high.

Galileo, on discovering Jupiter's satellites, was quick to realize that the orbital movements of the satellites conformed to the planetary laws that had been enunciated by his famous contemporary Johannes Kepler. This demonstration provided compelling evidence in support of the Copernican view that the Earth and the other planets revolved around the Sun, for Jupiter and his attendant satellites could be regarded as being a small-scale model of the solar system.

Galileo seized upon the idea that tables of the eclipses and occultations of Jupiter's satellites could provide a method for finding longitude—especially at sea. In response, therefore, to the handsome reward offered by King Philip III of Spain to anyone who invented a practical method for finding accurately the position of a ship when out of sight of land, Galileo set about the task of preparing suitable tables for the purpose.

Galileo's tables of predictions were insufficiently accurate for the intended purpose; and it was not until after knowledge of the perturbations of the satellites, due to their mutual interactions, had been acquired that predictions were sufficiently accurate for finding longitude.

The famous Italian astronomer J. D. Cassini applied himself to the problem of finding longitude by astronomical means and, in 1675, he prepared tables of predicted times of occultations and eclipses of Jupiter's satellites. The method was found to give good results for finding the longitudes of places on land.

The Danish physicist Roemer (1644–1710), in observing Jupiter's satellites at the Paris Observatory with the object of drawing up eclipse tables, discovered that predicted—and observed—times disagreed. He observed that the eclipses of the satellites were early compared with predicted times when Jupiter was relatively near to the Earth, and late when he was relatively remote from the Earth. This led him to the conclusion that light travels at a finite speed: and, moreover, he was able to make an approximate estimate of this speed.

In our own country Robert Hooke devoted some attention to drawing up tables of predictions of eclipses of Jupiter's satellites; but perhaps the most important work done in this connection was that of the celebrated Flamsteed.

John Flamsteed (1646–1719) acquired an interest in astronomy at an early age. Some papers he had written on the subject attracted attention, and he was appointed a member of a committee set up to report on a proposed method for finding longitude at sea. He became the first Astronomer Royal after the establishment of the Royal Observatory at Greenwich in 1675; and he is often regarded as being the first of the great English astronomical observers, being instrumental in introducing many improvements in observing methods. His *Historia Coelestis Britannica*, in three volumes published in 1725, some six years after his death, contains Flamsteed's catalogue of 3,000 stars.

Flamsteed drew up tables of eclipses and occultations of Jupiter's satellites, and contrived an instrument

> '. . . whereby with the sole help of the usual catalogue and the table of parallaxes of Jupiter's orbit, their [the satellites] distance from the axis of Jupiter may be found, to any given time within the compass of the year, and for any future year by the like tables.'

Numbers 151, 154, 165, 177, 178 of the *Transactions* of the Royal Society of London appear under Flamsteed's name; and all pertain to the problem of finding longitude from observations of eclipses of Jupiter's satellites. Flamsteed confessed it as part of his design to make

> '. . . our more knowing seamen ashamed of that refuge of ignorance, their idle and impudent assertion that the longitude is not to be found. . . .'

He goes on to say:

> 'Such of them as pretend to a greater talent of skill than others, will acknowledge that it might be attained by observations of the Moon, if we had tables that would answer her motions exactly: but after 2000 years we find the best tables extant erring sometimes 12 minutes or more in her apparent place which would cause a fault of ½ hour or 7½° longitude. I undervalue not this method for I have made it my business to get a large stock of lunar observations for the correction of her theory and as a groundwork for better tables, but the examination will be a work of long time and if we should afterwards attain what we seek, that it will be found much more inconvenient and difficult than that I propose by observing the eclipses of Jupiter's satellites.'

Flamsteed anticipated the seaman's objections to the method he proposed—and very real objections they were. The long telescope required for the observation would be almost unmanageable on board a lively ship at sea; and the difficulty there would be in distinguishing the satellites from one another: these were the principal faults of the method from the seaman's viewpoint. Flamsteed pointed out the success the French had accomplished using the method, and they managed with telescopes of '14 feet long at most'! He also remarked that '. . . difficulty cannot be known until the method is tried. . . .' and that '. . . use renders many things easy which our first thoughts conceived impracticable. . . .'

Transaction number 214 of the Royal Society is entitled *New and Exact Tables for the Eclipses of the First Satellite of Jupiter reduced to the Julian Stile and the Meridian of London.* This was the work of Cassini who remarked that the method of finding longitude from observations of eclipses of Jupiter's satellites had been used for all the principal ports of France. Cassini had employed his skill to make easy and obvious to all capacities the calculations for finding longitude by this method.

Tables of eclipses of Jupiter's satellites were provided in the very first *British Nautical Almanac*, which made its first appearance in 1765 for the year 1767. Maskelyne, in his explanation to the tables, stated that:

> 'The eclipses of Jupiter's satellites are well known to afford the readiest, and for general Practice, the best Method of settling the Longitudes of Places at land; and it is by their means principally that Geography has been so much reformed within a Century past.'

It had been hoped that means might have been found for providing a telescope suitable for use on board ship for observing the eclipses of Jupiter's satellites. Maskelyne described the trial he made, during a voyage to Barbados under the direction of the Commissioners of Longitude in 1763, of a marine chair designed by a Mr Irwin for the purpose of facilitating the observations. He wrote:

> '. . . but I could not derive any advantage from the use of it . . . and considering the great power requisite on a Telescope for making these observations well, and the Violence as well as the Irregularities of the Motion of the Ship, I am afraid the complete Management of a Telescope on Shipboard will always remain among the Desiderata.'

Maskelyne hastened to add, however, that he would not be understood to mean to discourage attempts founded upon good principles to get over this difficulty.

Many inventors, besides Irwin, attempted to provide the means of a steady platform suitable for use on board a rolling ship from which observations of Jupiter's satellites could be made. Commander Gould, in his work on the history of the marine chronometer, mentions several of these inventions. He also describes the steam-driven gyroscopic platform which was proposed in 1858 for the *Great Eastern*—that ill-fated leviathan of Brunel's.

The inclusion of tables of 'Eclipses of Jupiter's Satellites,' and diagrams of 'Configurations of the Satellites of Jupiter' in the

Nautical Almanac was aimed to induce keen nautical observers, in the interests of geography, to ascertain the longitudes of foreign places they visited from observations of Jupiter's satellites at a time when better methods were not available.

The method for finding longitude by eclipses of Jupiter's satellites involved observing the times of immersions (signifying the instants of disappearance of a satellite on entering the shadow of Jupiter), and emersions (signifying the reappearances of satellites on emerging from Jupiter's shadow). Comparisons of the times of observation with those given in the *Nautical Almanac* yielded the longitude of the place of observation.

For practical use at sea the method suffered, not only from difficulties of observing, but also because the eclipses do not occur instantaneously, this being due to the apparent diameters of the satellites not being inappreciable. Atmospheric effects also may affect the observations. Moreover, Jupiter is often near the Sun on the celestial sphere; and for long periods the method is not available owing to the planet not being favourably placed for observation. Many writers advocated the method for sea use; but practical seamen, and others who appreciated the difficulties of observing from a ship at sea, held little esteem for the method.

The French astronomer Lagrange (1736–1813) is credited with founding the dynamical theory of Jupiter's satellites; and the famous Laplace (1749–1827) is credited with the discovery of a remarkable numerical relationship between the satellites resulting from their mutual attractions.

The Swedish astronomer Wargentin, Secretary to the Royal Academy of Sciences at Stockholm, is noted for his tables of eclipses of Jupiter's satellites. His tables were published in the British *Nautical Almanac* for 1779 and for many succeeding years. From 1824 the predictions of the eclipses of Jupiter's satellites were from Delambre's tables; and from 1836 they were derived from Damoiseau's *Tables Ecliptiques des Satellites de Jupiter*.

4. LONGITUDE FROM OBSERVATIONS OF MOON OCCULTATIONS

The next astronomical method for finding longitude at sea, which is to demand our attention, is that in which star occultations by the Moon are employed.